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The influence of fly ash and foam contents on the properties of lightweight foamed concrete

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Abstract:

Due to rapid industrialization and modernization, a large number of both fly ash (FA) and ground granulated blast furnace slag (GGBFS), both by-products from thermal power plants and steel factories, are increasing day by day. Thus, recycling these industrial wastes to produce lightweight foamed concrete (LFC) was investigated in this study. Eight LFC mixtures were designed with different FA content and foam content to investigate their effect on the properties of LFC. Test results indicate that both FA and foam contents had a significant influence on the properties of LFC. The quality of LFC decreased with increasing foam content while the presence of FA improved its properties. The properties of LFC and its dry unit weight had a close relationship, and the correlation between them was described by linear regression. For example, high foam content resulted in more void volumes inside the LFC thus reducing its properties. Meanwhile, the presence of FA minimized the void volume and enhanced the LFC's properties. All LFCs in this investigation showed good quality, which were classified as grade M3.5-12.5 based on TCVN 9029:2017, which means they can be used as unburnt bricks with significantly low unit weight and thermal conductivity.

Keywords: **fly ash, foam content, GGBFS, lightweight foamed concrete.**

Classification number: **2.3**

Introduction

In recent years, the demand for electricity as well as steel during industrialization and modernization has been increasing rapidly in Vietnam. Many thermal power plants, iron factories, and steel factories have been built, which release a large amount of industrial waste. As estimated in 2019, about 16.4 million tons of FA and bottom ash were emitted from thermal power plants and a small part of which has been used to replace cement and fine aggregate in the production of concrete and unfired bricks [1]. However, the vast majority of these ashes are landfilled in a storage yard. The risk of overcapacity storage yards and leaks of these wastes are tremendous and can cause environmental pollution. On the other hand, approximately 1.12 million tons of GGBFS were generated in 2021 [2] and a part of which was used to partially replace cement for several important domestic construction projects. However, there are still huge amounts of FA and GGBFS that need to be recycled instead of being buried in storage yards. Moreover, the use of FA and GGBFS in the construction industry has been studied by many researchers around the world. Previous studies have proved that FA and GGBFS can be used as alternative binder materials in soil stabilization [3-6] residual granitic soil (RGS, controlled low strength materials [7, 8] coal ash, gypsum, red mud, paste and mortar [9, 10], and LFC [11-13]. Recycling FA and GGBFS in construction materials contributes to reducing the use of cement and minimizing their negative effects on the environment.

Foamed concrete was first described in 1923 as possessing outstanding advantages such as light weight and good sound and thermal insulation [14]. With its lighter weight, the use of LFC contributes to reducing static loads on a structure and thus reduces the sizes of structures and foundations. Using foamed concrete also conserves materials and reduces production, transportation, and construction costs. Therefore, LFC has received a lot of attention from researchers around the world in recent years. However, some studies have indicated that the biggest challenge to the widespread use of LFC is that its compressive strength is too low, so its application is still limited [15, 16] high workability (flowing and self-compacting). Currently, it has only been used as insulating walls, heat resistant roofs, and lightweight brick instead of unburnt bricks. In recent years, several studies have investigated the use of industrial wastes such as FA and GGBFS in producing

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LFC [11-13]. However, either FA or GGBFS alone were used in these previous studies and works on the combination of both FA and GGBFS in the production of LFC are lacking.

The quality of LFC is affected by many factors such as curing conditions, quality of original composition materials, mixture proportion, and its dry density [17]. Among these factors, dry density has the most impact on LFC's properties [17-19]. However, most previous studies have only focused on the effect of dry density on the compressive strength of LFC and its effect on other properties still needs to be investigated. Therefore, in this study, both FA and GGBFS were used to replace 40-60% of cement in producing LFC. The effect of foam and FA contents on the engineering properties of LFC such as compressive strength, ultrasonic pulse velocity (UPV), water absorption, and thermal conductivity were investigated. The correlation between LFC's properties and its dry unit weight were established. The microstructure of LFC was also investigated using scanning electron microscopy (SEM).

Materials and experimental programs

Materials

A blend of cement, FA, and GGBFS was used as the binder in this study and their properties are given in Table 1. The specific gravity of cement is the highest, followed by GGBFS and FA. Cement type PCB40 was sourced from Nghi Son Company, while FA and GGBFS were taken from the Nghi Son Coal Power Plant and Hoa Phat Steel Factory, respectively. The main compositions of cement and GGBFS are SiO_2 and CaO, meanwhile, the main compositions of FA are SiO_2 and Al_2O_3. Fly ash with a summation of SiO_2, Al_2O_3, and Fe_2O_3 above 70% is classified as type-F based on TCVN 10302:2014 [20]. The natural appearance and morphology of cement, FA, and GGBFS observed by SEM are shown in Fig. 1. According to Fig. 1, the cement particle size is the largest among the three binder materials. While cement and GGBFS have irregular shapes, FA is spherical.

Table 1. Properties of binder materials.

Categories		Cement	FA	GGBFS
Physical properties	*Specific gravity*	3.12	2.16	2.84
	Loss on ignition (%)	0.5	6.9	0.4
Chemical composition (wt.%)	SiO_2	22.3	55.7	36.9
	Al_2O_3	6.7	21.7	12.4
	Fe_2O_3	4.7	6.6	-
	CaO	55.5	1.1	30.7
	MgO	2.4	2.2	14.8
	SO_3	1.3	-	0.4
	Na_2O	0.6	0.2	0.3
	K_2O	0.7	2.1	0.9
	TiO_2	0.7	0.7	0.4

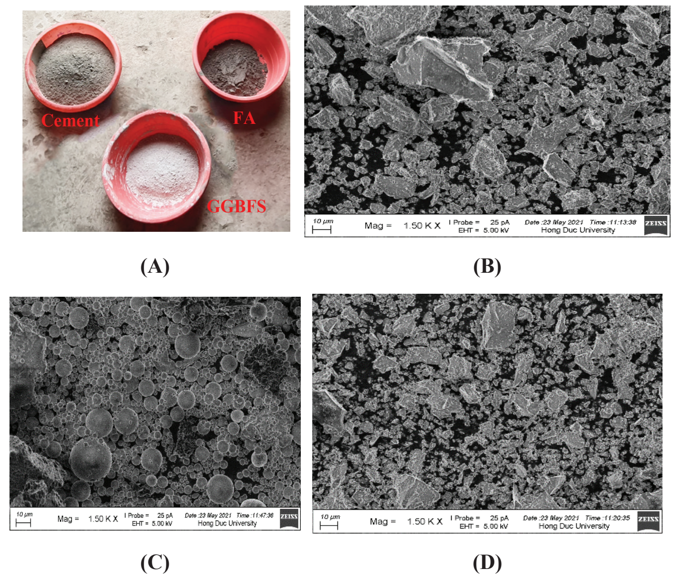


Fig. 1. (A) Natural appearance of binder materials and SEM micrographs of (B) cement, (C) FA, and (D) GGBFS.

Other compositions of LFC are river sand, tape water, superplasticizer (SP), and foam. The sand had particle sizes ranging from 0.15 to 0.63 mm and a density of 2680 kg/m^3 was used as the fine aggregate. SP, with a density of 1.05±0.2 kg/m^3 was utilized to reduce the water content and ensure the flowability of fresh concrete. A foaming agent named EABASSOC was used with water in a ratio of 1/40. Foam was created by using a foam generator as shown in Fig. 2.

Fig. 2. Foam generation.

Mix proportions

Eight LFC mixtures were designed with the proportions presented in Table 2. The GGBFS content was equal to 30% of the total binder by weight, while the FA contents are 10 and 30% in M10 and M30 mixtures, respectively. Previous studies have indicated that increasing the sand content results in a reduction of the compressive strength of LFC [21, 22]. Thus, the amount of sand in this investigation was taken as 0.25 times the total binder content (cement, FA,

Table 2. Mixture proportions.

No.	Mixture	W/B	Ingredient proportions (kg/m³)						Foam (m^3)
			Cement	*FA*	*GGBFS*	*Sand*	*Water*	*SP*	
1	M10-1	0.22	571.7	95.3	285.9	238.2	211.8	1.5	0.37
2	M10-2		533.8	89.0	266.9	222.4	197.7	1.4	0.41
3	M10-3		469.0	78.2	234.5	195.4	173.7	1.3	0.48
4	M10-4		456.4	76.1	228.2	190.2	169.0	1.2	0.50
5	M30-1	0.2	402.1	301.5	301.5	251.3	201.0	1.4	0.33
6	M30-2		380.9	285.7	285.7	238.0	190.4	1.3	0.37
7	M30-3		334.0	250.5	250.5	208.8	167.0	1.2	0.44
8	M30-4		315.3	236.5	236.5	197.0	157.6	1.1	0.47

and GGBFS). The SP content and ratio of water to binder were selected so that the concrete mixtures had sufficient workability. It is noticed that the workability of the paste (mixture of binder, sand, water, and SP) is very important to the successful fabrication of the samples. If the paste is too dry or too wet, the samples will be segregated or have high-volume shrinkage after casting. Based on the extensive experiment, the paste has suitable workability as determined by a flow diameter of around 18±2 cm as measured in accordance with TCVN 3121:2003 [23].

The first group included four mixtures (from M10-1 to M10-4) and was designed with a FA content of 10%, a water-to-binder (W/B) ratio of 0.22, and an SP content equal to 0.16% of the total binder. The second group consisted of four mixtures (from M30-1 to M30-4), which was designed with an FA content equal to 30% of the total binder. As mentioned above, the spherical particles of FA will yield an increase in paste workability [24] tentatively named Fa-RmLG, was made from fly ash (Fa, thus the W/B ratio and SP content in these mixtures were, respectively, reduced to 0.20 and 0.14%. Mixtures M10 and M30 denote those with 10 and 30% FA, respectively. The numbers after M10 and M30, from 1 to 4, denote the mixture numbers, which were designed with varying foam content. The objective of this study is to examine the effect of foam and FA contents on the engineering properties of LFC. The correlations between the properties of LFC and its unit weight are also established.

Sample preparation and test methods

All dry materials were mixed first, then water and SP were added and mixed until a homogeneous paste was obtained. The flow diameter of the paste was immediately checked after mixing. If a flow diameter of 18±2 cm was achieved, the foam was added and mixed until the mixture was homogeneous. If the flow diameter was not satisfied, SP was used to adjust the flowability of the paste. It was noticed that the foam content used in practice was higher than the presented value in Table 2 because the foam bubbles were broken during the experiment. The steel mould, with a dimension of 100×100×100 mm, was used for sample casting. The samples were de-moulded 24 hours after casting and stored under ambient air conditions until testing day.

The unit weight of fresh concrete was checked immediately after mixing, while the dry unit weight of hardened concrete was measured under TCVN 9030:2017 [25] at 28 days. Compressive strength and water absorption of LFC were also tested based on TCVN 9030:2017 [25], while the UPV test was conducted in compliance with TCVN 9357:2012 [26]. Thermal conductivity was directly measured using ISOMET-2014 equipment. The compressive strength and UPV were measured at 7, 14, and 28 days, while the water absorption and thermal conductivity were measured at 28 days. The reported value herein is the average value of at least three measurements. After breaking from compression testing at 28 days, several pieces from the samples were collected for microstructure examination using SEM. The compressive strength, UPV, and thermal conductivity tests of LFC are illustrated in Fig. 3.

Results and discussion

Unit weight

The fresh and dry unit weight of the LFC mixtures are presented in Table 3. The FA content and foam volume are also given in Table 3 for comparison and discussion. In general, the dry unit weight of LFC was found to be 86-92% of its fresh unit weight. The loss of unit weight in

(A) (B) (C)

Fig. 3. (A) Compression, (B) UPV, (C) thermal conductivity test equipment.

Table 3. Unit weight of LFC.

No.	Mixture	FA content (%)	Foam (m^3)	Fresh unit weight (kg/m^3)	Dry unit weight (kg/m^3)	Classification based on TCVN 9029:2017
1	M10-1	10	0.37	1404	1278	D1300
2	M10-2		0.41	1311	1169	D1200
3	M10-3		0.48	1152	1063	D1100
4	M10-4		0.50	1121	1030	D1000
5	M30-1	30	0.33	1459	1313	D1300
6	M30-2		0.37	1382	1223	D1200
7	M30-3		0.44	1212	1103	D1100
8	M30-4		0.47	1144	986	D1000

the dry condition is due to the evaporation of water that existed in fresh concrete. In each group, the unit weight of LFC decreased with increasing foam content. For the M10 group, the dry unit weight reduced from 1278 to 1121 kg/m^3 while the foam volume increased from 0.37 to 0.50 m^3. Similarly, a reduction in the dry unit weight of the M30 group, from 1313 to 986 kg/m^3, corresponded to the foam content increasing from 0.33 to 0.47 m^3. Notably, the mixtures in the two groups M10 and M30 were designed with a similar dry unit weight, which was identified with the same classification as in TCVN 9029:2017 [27]. For those with similar unit weights, for example M10-1 and M30-1, the foam volume of M30-1 was lower than that of M10-1. It was noticed that the proportion of FA in the M10 and M30 mixtures were, respectively, 10 and 30% of the total binder. The specific gravity of FA was significantly lower than that of cement (Table 1). With the same content, the volume of FA was larger than that of cement. Thus, as increasing the FA content yields a reduction in the void volume of LFC, and the foam volume is consequently reduced.

Compressive strength

The compressive strength developments of the M10 and M30 mixtures versus curing time are plotted in Figs. 4A, 4B, respectively. In each group, the compressive strength increased with a reduction in foam content and increasing curing time. As the hydration products continuously form over time; consequently, the compressive strength of concrete also increases with time. On the other hand, a high foam volume results in a high void volume and high porosity of the concrete sample, which causes a reduction in compressive strength. This finding is in line with reports from previous studies [17-19]. The compressive strength of the M10 mixtures reduced from 16.3 to 8.4 MPa, meanwhile, those of the M30 mixtures dropped from 21.4 to 6.4 MPa. With a similar dry unit weight, the compressive strength of an

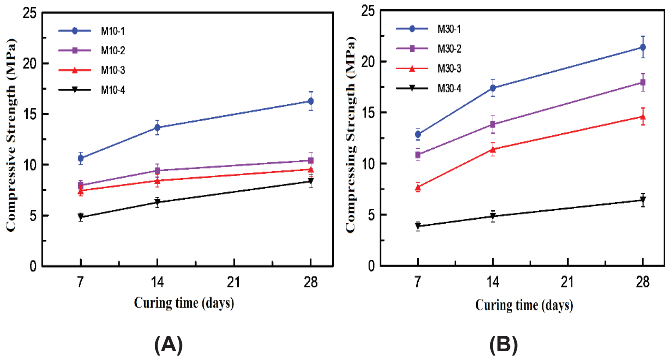


Fig. 4. Compressive strength of the (A) M10 and (B) M30 mixtures.

M30 mixture is higher than that of the corresponding M10 mixture, except for mixture M30-4. Notably, even M10 and M30 mixtures have a similar unit weight, but the foam contents of the M30 mixtures are lower than that in corresponding M10 mixtures. The high FA content in M30 mixtures is associated with the low foam volume used in M30 mixtures as mentioned previously because of the lower specific gravity of FA compared to that of cement. Consequently, the void volumes in the M30 mixtures are lower than that of their corresponding M10 mixtures, which results in higher compressive strength. However, M30-4 had a lower compressive strength than M10-4 because the dry unit weight of M30-4 is actually lower than that of M10-4. It is noted that the dry unit weight is the main factor affecting the properties of LFC [17-19]. Therefore, a correlation between the 28-day compressive strength and dry unit weight of LFC is established as shown in Fig. 5. Regardless of water-to-binder ratio and foam and FA contents, the correlation between compressive strength and dry unit weight can be described by linear regression with a high coefficient of determination ($R^2 = 0.82$).

With a 28-day compressive strength of above 15 MPa, mixtures M10-1, M10-2, and M30-1 can be used for semi-structure in practice, while other mixtures can be used as non-structure such as lightweight bricks instead

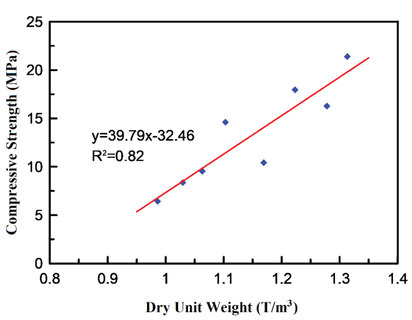


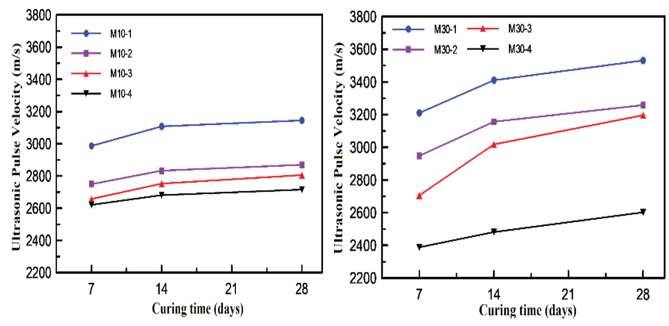
Fig. 5. The correlation between compressive strength and dry unit weight.

of unfired bricks. Based on TCVN 9029:2017 [27], with compressive strength ranging from 6.4 to 21.4 MPa, the LFC in this investigation is classified as grades M3.5 to M12.5, which is indicated as a high grade of LFC. It is also noticed that most popular cement and fired clay bricks used in practice have a compressive strength of around 5 to 7.5 MPa and a unit weight of around 1800 to 2500 kg/m^3. All LFCs in this study have similar or even better compressive strength than that of conventional cement and fired clay bricks, but a significantly lower unit weight. Therefore, the LFCs in this study show a huge potential to be utilized as unfired bricks in practice.

Ultrasonic pulse velocity

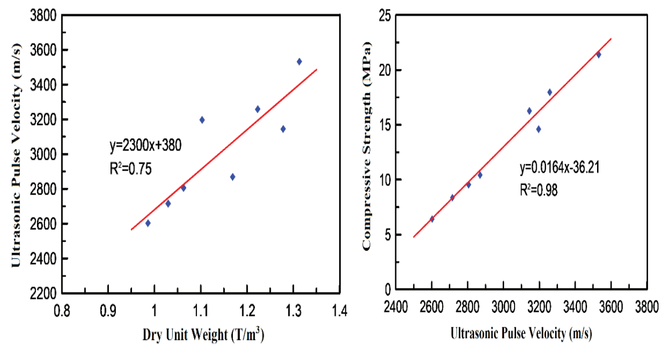
Figures 6A and 6B show the UPV values of the M10 and M30 mixtures, respectively. Similar to compressive strength, the UPV values of LFC increased with curing time and reduced with increasing foam content. It has been established that the UPV value and density of concrete have a close relationship [28]. Furthermore, the UPV value is also related to the compressive strength value [29]. As hydration products were generated during the curing time, the resulting product had high density, high compressive strength as well as high UPV value. In each group, the UPV value of LFC samples reduced with increasing foam content. The 28-day UPV value of the M10 mixtures decreased from 3145 to 2715 m/s when the foam content increased from 0.37 to 0.50 m^3. Similarly, those values of the M30 mixtures decreased from 3531 to 2602 m/s as the foam content changed from 0.33 to 0.47 m^3.

In general, with higher FA content, the M30 mixtures showed a higher UPV value than the corresponding M10 mixtures, except for M30-4. As mentioned above, the presence of FA had a positive effect of decreasing the void volume inside LFC, thus improving the UPV value. It was noticed that the dry unit weight of M10-4 was higher than that of M30-4 (as seen in Table 3). Both FA and foam contents are related to the dry unit weight of LFC, thus affecting the UPV value. With higher dry unit weight, M30-1, M30-2, and M30-3 showed higher UPV than M10-1, M10-2, and M10-3, respectively. This means that the UPV value of LFC strongly depends on its dry unit weight, which is in agreement with a previous study [28]. The correlation between UPV and dry unit weight of LFC can be described by linear regression as shown in Fig. 7A. Although UPV tests have been used to evaluate the relative quality of normal concrete [18, 19], it is rarely applied to LFCs in the literature. Most of the LFC in this study can be used as unburnt bricks with significantly low unit weight as mentioned earlier. Based on previous studies [30, 31], most unburnt bricks had a UPV value ranging from 1700 to 2920 m/s. Indeed, with UPV values ranging from 2602 to 3531 m/s, which are higher than previously reported values [30, 31], all of the LFCs in this investigation can be classified as good quality. The correlation between the compressive strength and UPV of LFC is also presented in Fig. 7B, which helps to predict the compressive strength of LFC when compression tests are not allowed.



(A) (B)

Fig. 6. Ultrasonic pulse velocity of the (A) M10 and (B) M30 mixtures.



(A) (B)

Fig. 7. The correlation between (A) UPV and dry unit weight and (B) compressive strength and UPV.

Water absorption

Water absorption of the M10 and M30 mixtures at 28 days are shown in Figs. 8A and 8B, respectively. In each group, the mixture with high foam content showed a high water absorption capacity. The water absorption of the M10 mixtures increased from 6.7 to 10.1% when foam content was increased from 0.37 to 0.50 m^3. For the M30 mixtures, the water absorption increased from 5.7 to 10.2% as the foam content increased from 0.33 to 0.47 m^3. Generally, the water absorption of the M30 mixture was slightly lower than that of the corresponding M10 mixture because the former had a lower foam content than the latter. The high FA content in the M30 mixtures also helped to reduce water absorption, except for M30-4. Again, it is noted that M30-4 had a lower dry unit weight than M10-4 (as shown in Table 3). A linear equation is used to illustrate the relationship between the water absorption of LFC and its dry unit weight as shown in Fig. 9. For cement-sand-based LFC produced by Abd and Jarullah [18], the concrete samples with a unit weight of 1200 kg/m^3 had a water absorption of about 26%, which was significantly higher than those values of LFC produced in the present study. The use of FA in the present study contributes to reducing the void volume inside of concrete, thus, the water absorption value in comparison to reported values studied by Abd and Jarullah [18] was lower. It is also noticed that all LFCs in the present study have a water absorption of below 16%, which satisfies a requirement for them to be used as unburnt bricks [32].

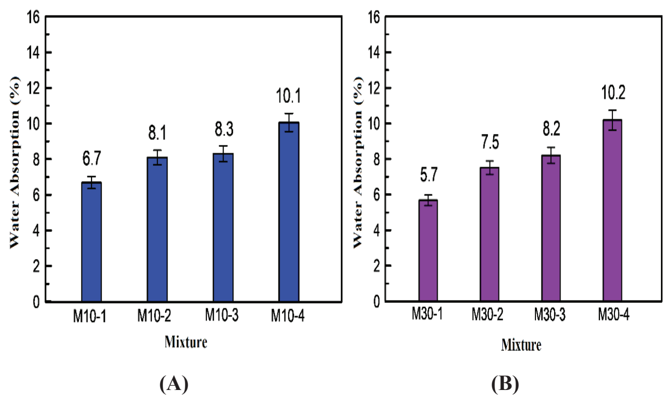


Fig. 8. Water absorption of the (A) M10 and (B) M30 mixtures.

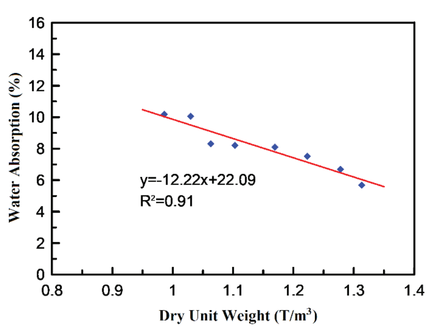


Fig. 9. The correlation between water absorption and dry unit weight.

Thermal conductivity

The thermal insulation ability of LFC is expressed through the thermal conductivity value, which is plotted in Fig. 10. For the M10 and M30 mixtures, the thermal conductivity ranged from 0.401-0.644 W/mK and 0.387-0.899 W/mK, respectively. According to Fig. 10, the thermal conductivity decreased with increasing foam content. In general, the M30 mixture had a higher thermal conductivity value than the corresponding M10 mixture, except for M30-4. This phenomenon is due to the higher FA content used in the M30 mixtures than that used in the M10 mixtures. H. Uysal, et al. (2004) [33] indicated that the density of concrete has a strong effect on its thermal conductivity. The higher the density, the lower the thermal conductivity. Regardless of FA and foam contents, a mixture with higher dry unit weight yielded a higher thermal conductivity. The effect of the dry unit weight of LFC on its thermal conductivity in this study can be described by linear regression as shown in Fig. 11. On the other hand, the thermal conductivity of normal concrete is around 1.2-1.5 W/mK [33], which is significantly higher than that of LFC in this investigation. Therefore, with low thermal conductivity, all the LFCs in this study can be used as thermal insulation materials.

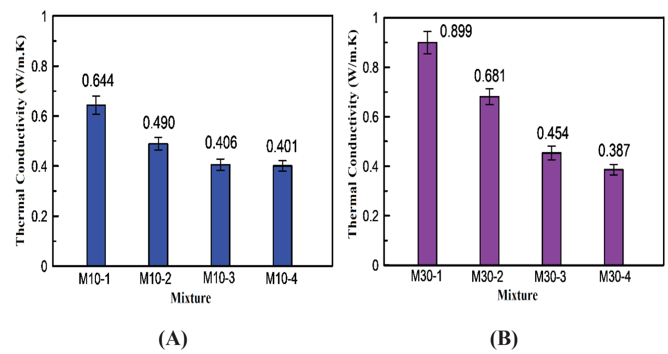


Fig. 10. Thermal conductivity of the (A) M10 and (B) M30 mixtures.

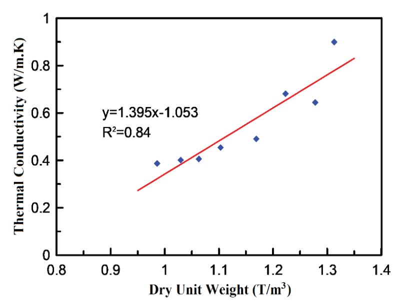
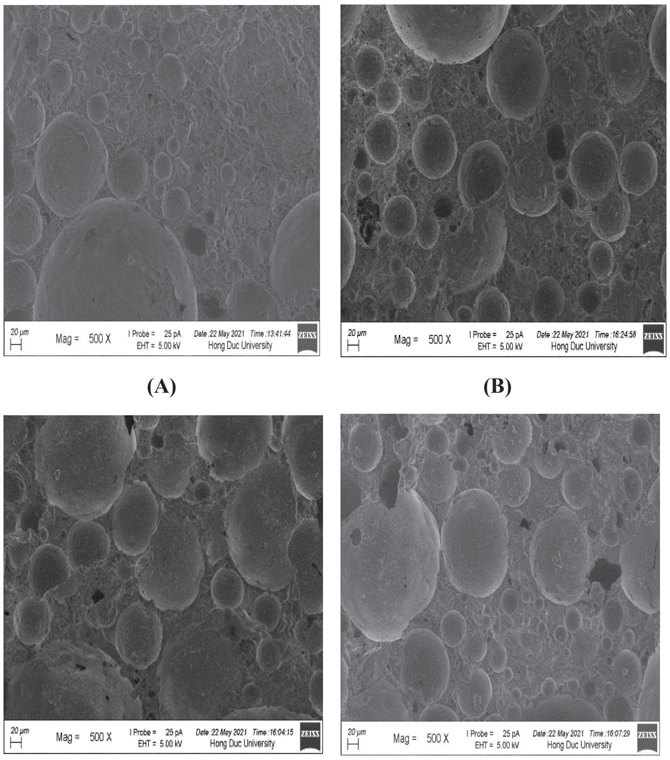


Fig. 11. The correlation between thermal conductivity and dry unit weight.

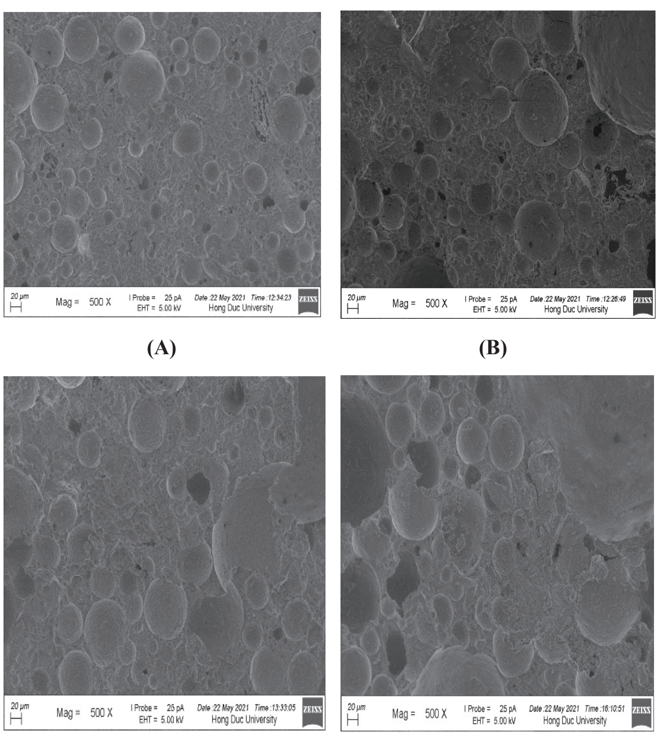
SEM observation

Figures 12 and 13 show changes in the microstructure morphology of the M10 and M30 mixtures, respectively. When foam content was increased, more spherical shapes were observed. These spherical bubbles increased the void volume inside the LFC, thus, they have a negative effect on LFC properties such as unit weight, compressive strength, UPV, water absorption, and thermal conductivity as mentioned earlier. On the other hand, the bubbles in Fig. 13 are smaller than those in Fig. 12. It should be noted that the M10 and M30 mixtures were designed with FA contents equal to 10 and 30% of the total binder materials (as shown in Table 2). With a low



(A) (B) (C) (D)

Fig. 12. SEM observation of (A) M10-1, (B) M10-2, (C) M10-3, and (D) M10-4.



(A) (B) (C) (D)

Fig. 13. SEM observation of (A) M30-1, (B) M30-2, (C) M30-3, and (D) M30-4.

specific gravity, FA has many more particles than cement. These FA particles will minimize the void volume inside the LFC, thus the sizes of bubbles in M30 mixtures are smaller than that in M10-mixtures. Consequently, if the void is reduced, the properties of LFC will increase. These findings prove that both foam and FA contents have a significant influence on the properties of LFC.

Conclusions

In this study, eight LFC mixtures were designed with various FA and foam contents. The influence of both FA and foam contents on the LFC's properties were investigated. Some main conclusions may be drawn based on the above experimental program, as follows:

(1) Dry unit weight, compressive strength, UPV, and thermal conductivity of LFC decreased, while its water absorption capacity increased with increasing foam content.

(2) The presence of FA contributed to reducing void volume inside the LFC, thus improving its properties.

(3) The dry unit weight of LFC was significantly impacted by both foam and FA contents. Meanwhile, LFC's properties strongly depended on its dry unit weight. Thus, the correlation between the properties of LFC and its dry unit weight were established.

(4) Under SEM observation, high foam content resulted in more bubbles that reduced the properties of the LFCs. Meanwhile, the use of high FA content minimized the size of the bubbles, which improved the properties of LFC.

(5) All LFCs in this investigation were classified as grade M3.5-12.5 based on TCVN 9029:2017 indicating a good, lightweight foamed concrete. These LFCs can be used instead of unfired bricks with significantly low unit weight and thermal conductivity.

COMPETING INTERESTS

The authors declare that there is no conflict of interest regarding the publication of this article.

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